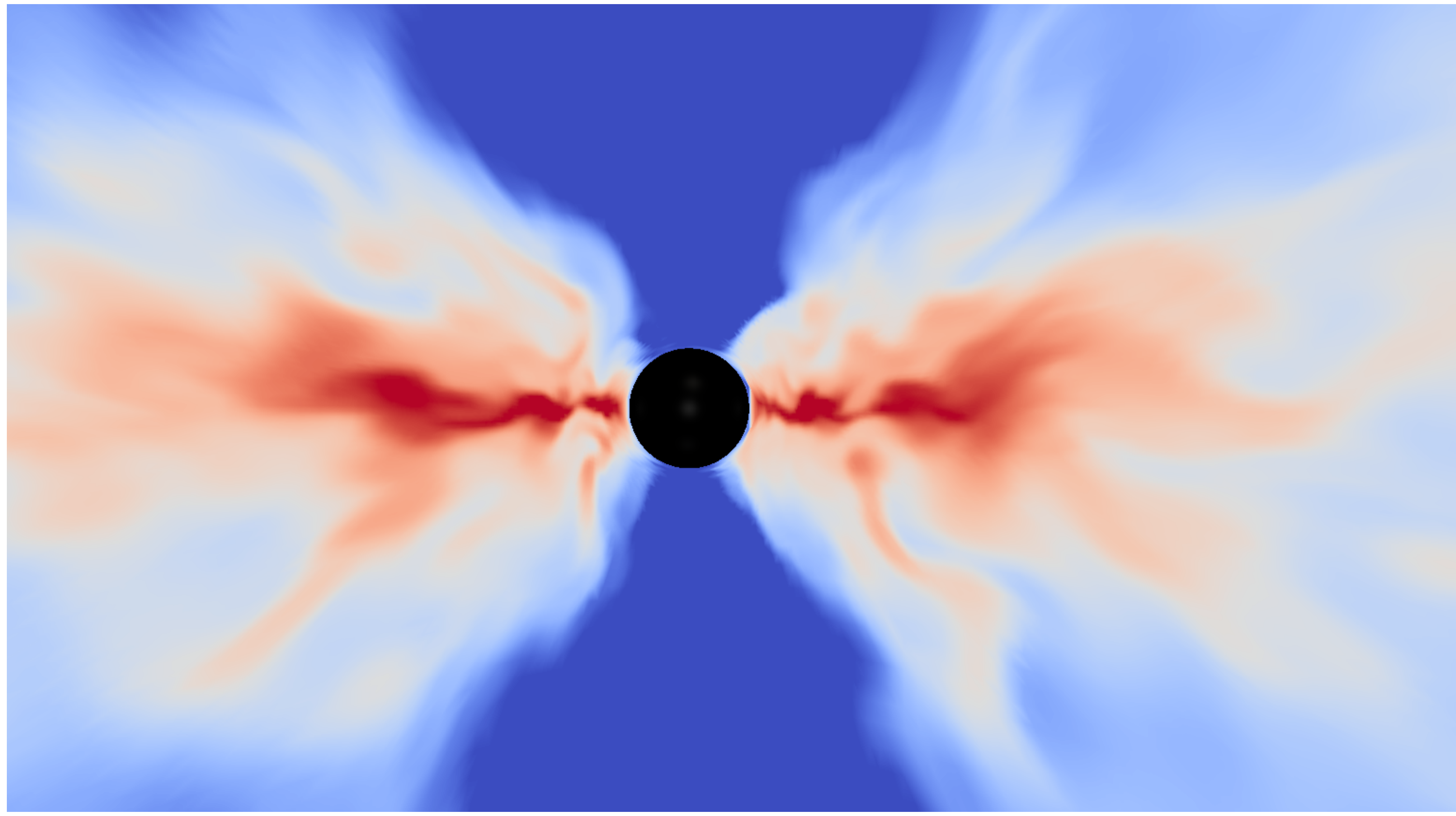
Post-merger evolution of compact binaries

Numerical relativity at WSU
GWANW 2021



Matthew Duez, Dept. of Physics and Astronomy, WSU Tuesday, June 29, 2021

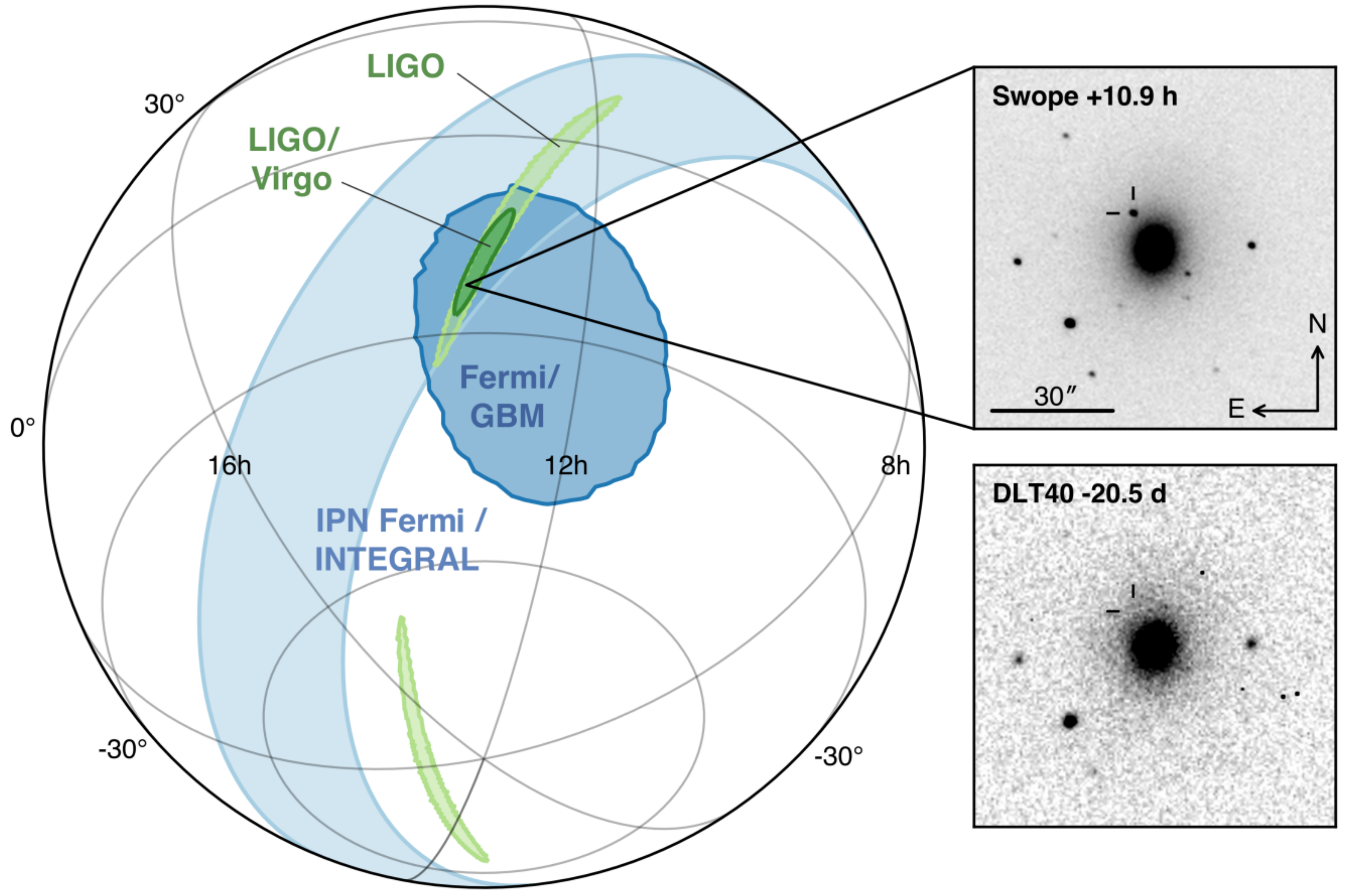
Neutron Star-Neutron Star (NSNS) and Black Hole-Neutron Star (BHNS) binaries

Motivation

- Inspiral gives of *gravitational waves*. Merger/post-merger gives off *electromagnetic waves*.

- IR/optical/UV kilonova from outflows (e.g. tidal ejecta, disk winds)

- GRB from relativistic jet (e.g. from disk accreting onto black hole)



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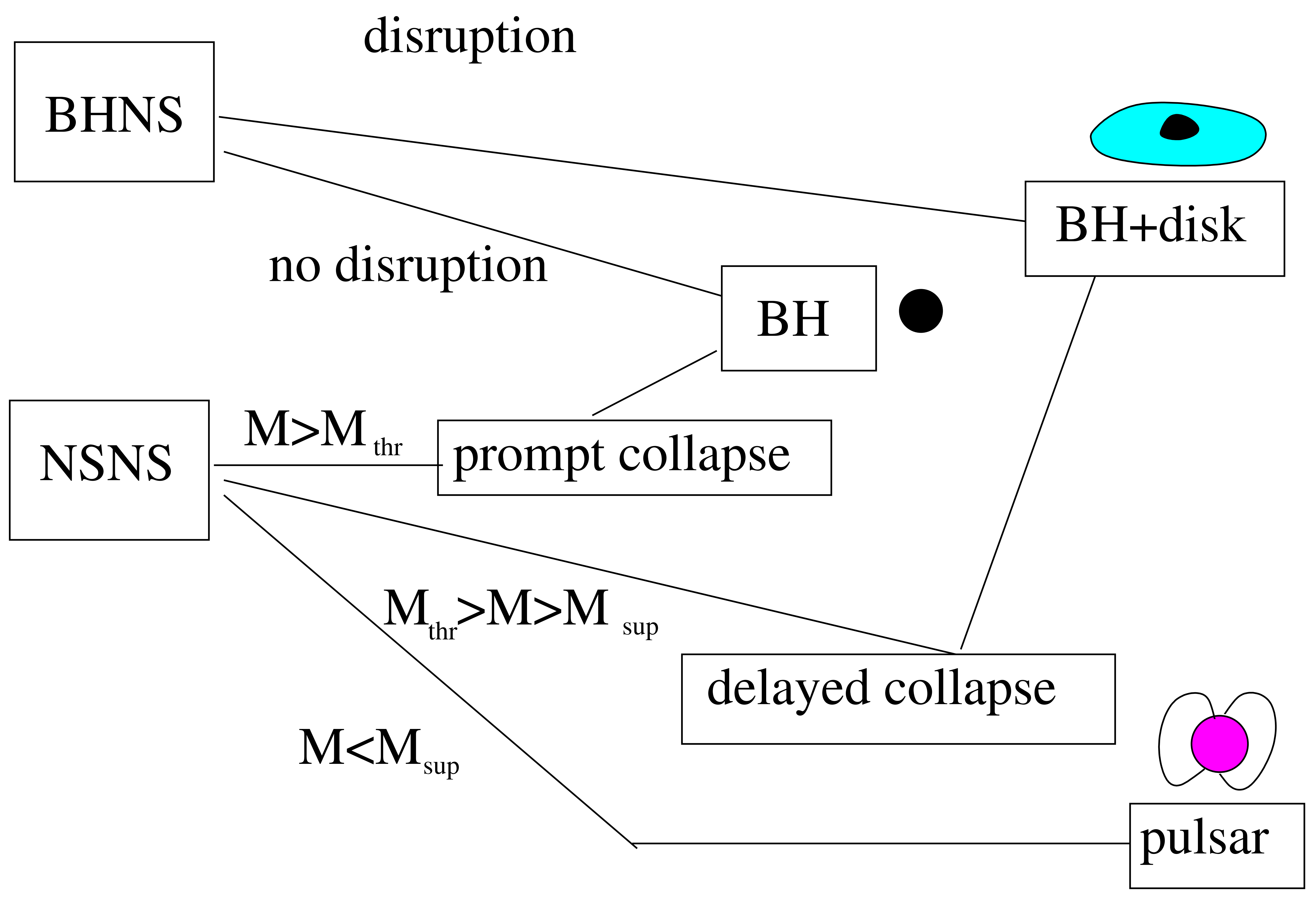
From ApJL 848:L12, 2017

Post-merger evolution channels



Secular effects and their timescales

- quasi-equilibrium NS remnant (for NSNS mergers), disk (for either) secular evolution driven by
- turbulence → angular momentum transport $\tau_{\text{visc}} \propto \dfrac{R^2\Omega}{\alpha c_s^2}$,

  ~10ms for remnant, ~100ms for disk
- neutrino cooling $\tau_\nu \sim E/L_\nu$, ~sec for remnant, ~10ms for disk
- remnants come to uniform rotation, then cool
- disks come to thermal equilibrium, then accrete and expand

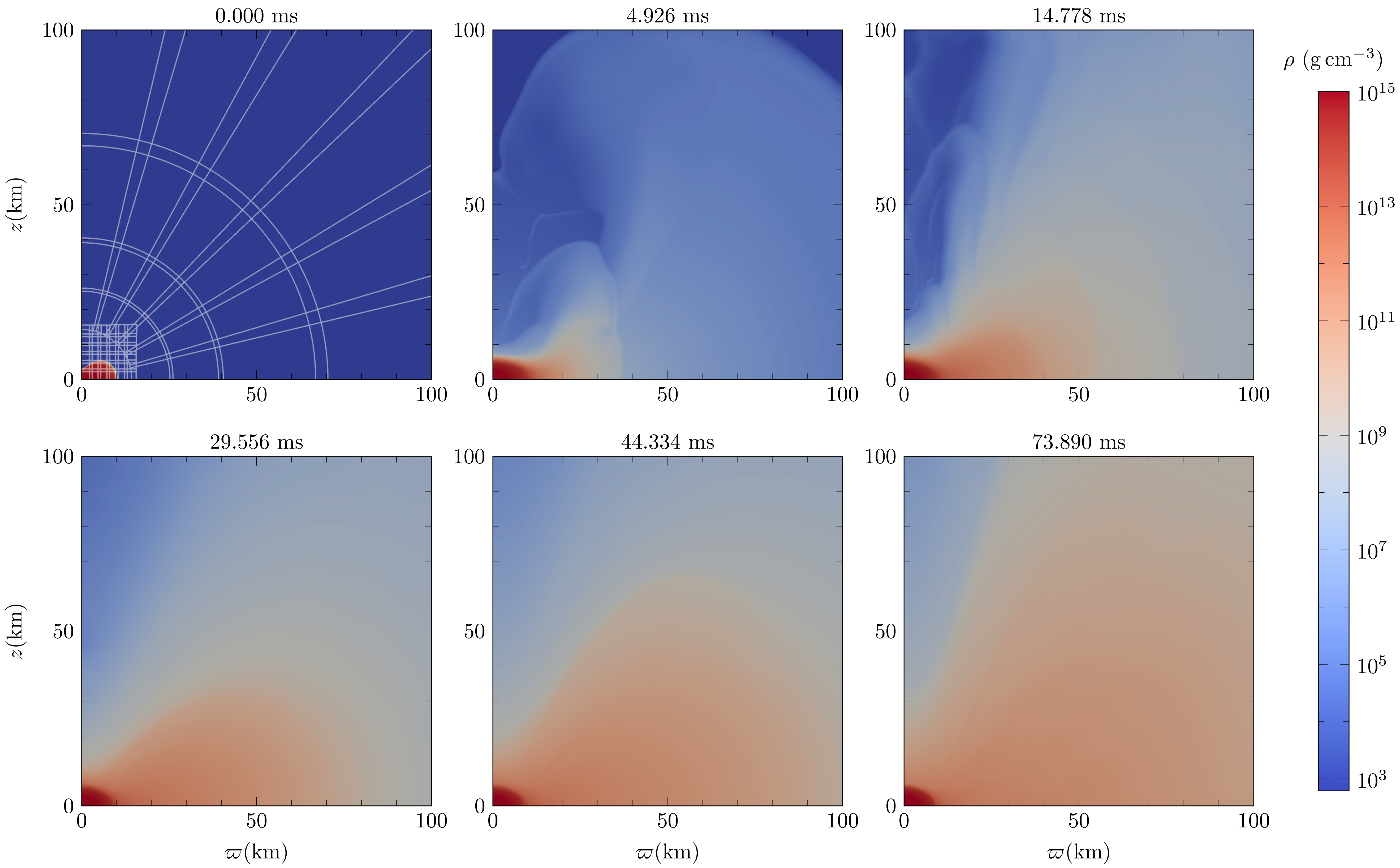
Challenge 1: disparity of timescales

- Compare: $\tau_{\rm dynamical} \sim$ ms
- Disk winds only begin after ~sec, when disk becomes advective.
- Delayed collapse between 10ms and sec.
- Studies of these late times must be 2D (axisymmetric)
  e.g. Fernandez *et al* (2013, 2018), Fujibayashi *et al* (2017)
- Momentum transport modeled by shear viscosity.

Axisymmetric 2D simulations with SpEC

Jesse *et al* (2020)

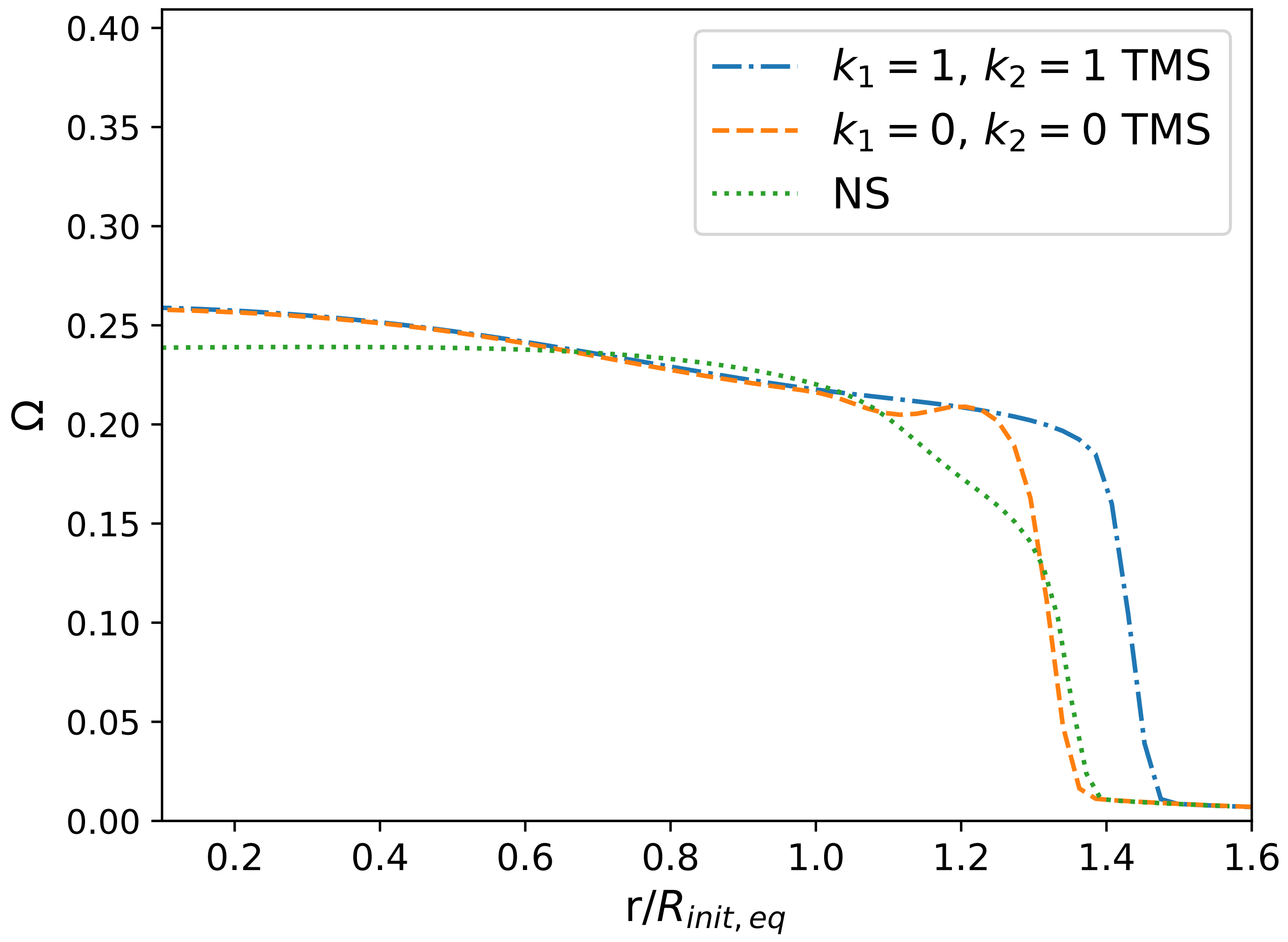
- Spectral Einstein Code (3D) already uses multipatch methods (each patch has its own local coordinates) and has equations in covariant form. Can use this to set 3rd direction=ϕ, evolve on 2D grid
- can deform and combine patches
- implemented hydro, MHD, viscosity, M1 neutrino transport

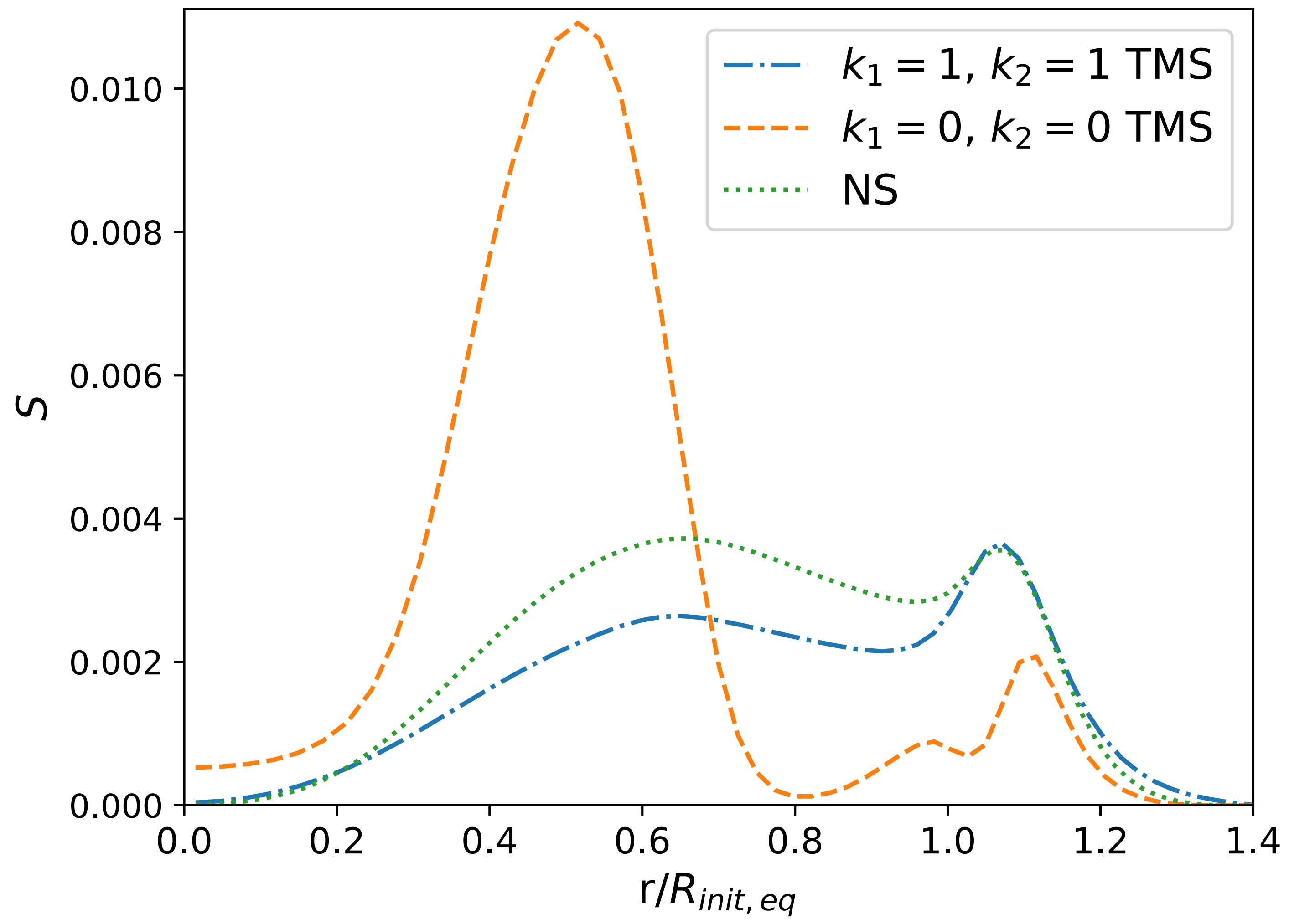


Momentum (and other) transport with SpEC

Duez *et al* (2020)

- Viscosity models momentum transport from subgrid scale turbulence.
- Two implementations in current NR codes: SACRA & Radice
- We compared the two methods for differentially rotating stars and BH accretion disks
- We add turbulent heat conduction and particle diffusion.





Challenge 2: Neutrino Transport

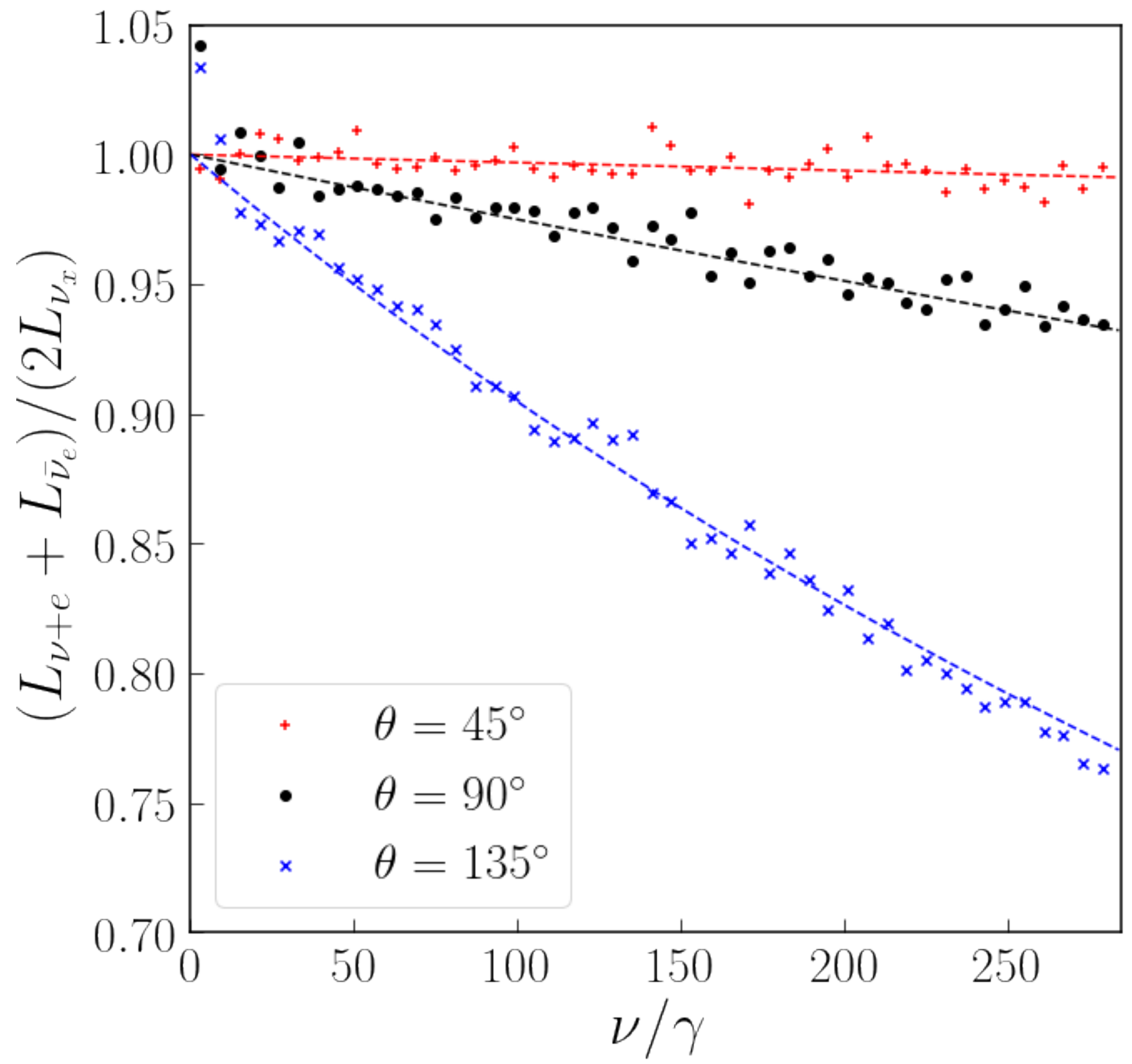
Why it's so hard

- Neutrinos cool remnant & disk, heat outflows, alter composition of disks & outflows
- neutrino distribution function: $dN = f(x^i, p_i, t) d^3x d^3p$
- Boltzmann transport equation: $p^\alpha \left[\frac{\partial f}{\partial x^\alpha} - \Gamma^\beta{}_{\alpha\gamma} p^\gamma \frac{\partial f}{\partial x^\beta} \right] = \left[\frac{df}{d\lambda} \right]_{\text{collisions}}$
- If optical depth $\tau_\nu \sim L/\ell_{\nu\ \mathrm{MFP}} \ll 1$, geometric optics, ray tracing
- If $\tau_\nu \gg 1$, radiative diffusion, moment closure schemes accurate
- Unfortunately, must deal with both and with $\tau_\nu \sim 1$.

Neutrino transport with SpEC

Foucart *et al* (2020), Foucart *et al* (2021)

- SpEC implemented leakage [Deaton *et al* (2013)], then M1 [Foucart *et al* (2015,2016)]. "Grey" schemes—sacrifice knowledge of energy spectrum (except for avg); Because of closure approx, won't converge to true solution. Especially bad on poles.
- New Monte Carlo scheme [Foucart (2020, 2021)] samples full distribution using packets of neutrinos —created, propagated, absorbed, scattered
- Implicit MC trick to avoid stiffness at high opacity (reduce κ_ν, η_ν; enhance scattering for right diffusion)

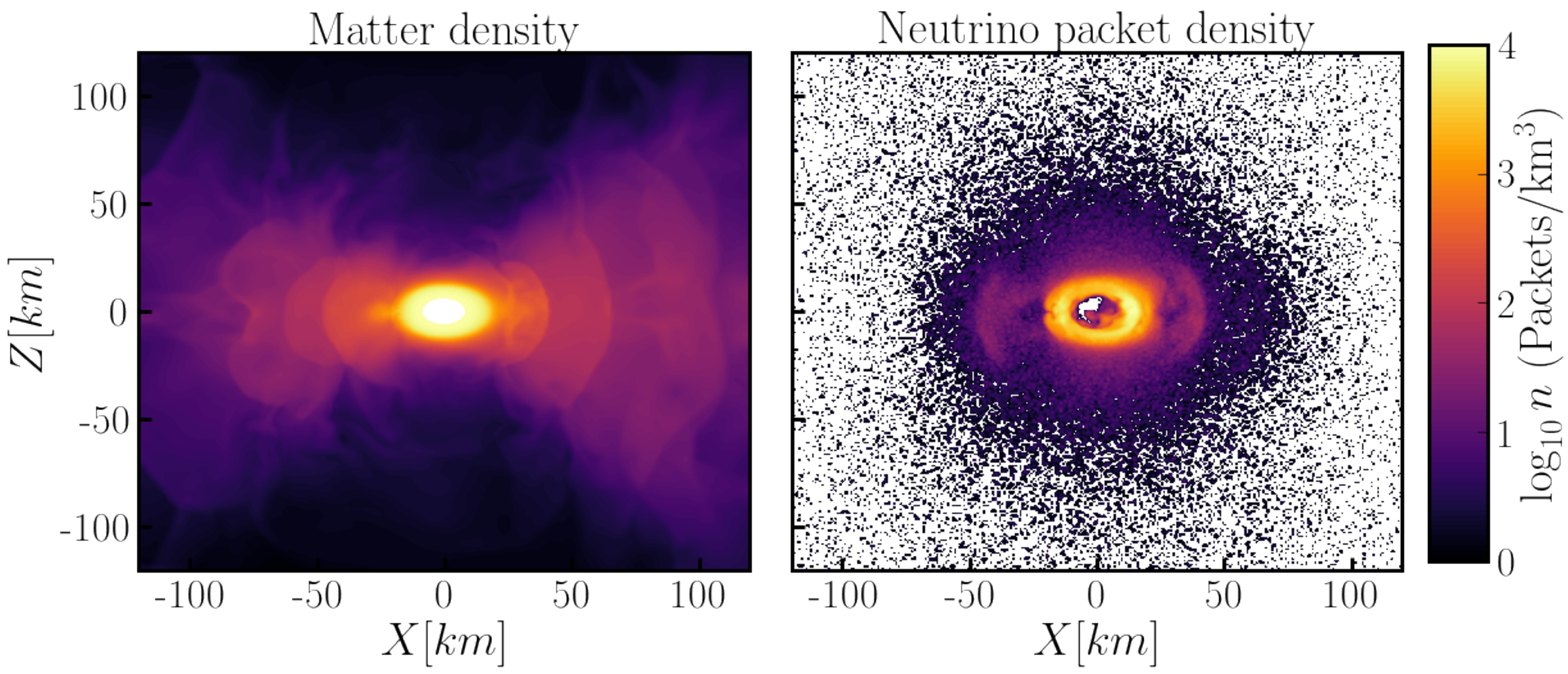


Crossing beams test for pair annihilation from Foucart et al (2021)

First Monte Carlo simulations

A binary neutron star merger

- evolve to 5ms post-merger;
  compare M1 vs. MC
- find M1 gets ejecta Y_e and v to 10%; 20% error in L_{ν_e} and $L_{\overline{\nu}_e}$
- factor of 2 error in L_{ν_x}



Future work

- We have a bank of BHNS and NSNS simulations going ~5ms post-merger.
- Now continue them in 2D with viscosity, neutrino transport to ~few seconds
- Observe remnant evolution; measure outflows, heating from neutrino pairs
- Later on: find a way to add large-scale magnetic field effects